International Society for Environmental Information Sciences 2010 Annual Conference (ISEIS)

Discharge-salinity relationships in Modaomen waterway, Pearl River estuary

Zhiming ZHANG, Baoshan CUI*, Hui ZHAO, Xiaoyun FAN, Honggang ZHANG

School of Environment, Beijing Normal University, State Key Joint Laboratory of Environmental Simulation and Pollution Control, No. 19 Xinjiekouwai Street, Beijing 100875, China

Abstract:

There are many parameters determining salt intrusion in alluvial estuaries, including river discharge, channel shape, tidal forcing. In this paper, according to a well-tested theory for the calculation of salt intrusion in estuary regions, the salt intrusion length can be computed by the model that drives from this well-tested theory. There is an analytical method that presented for the salt intrusion in a funnel-shaped estuary. The method is tested against monitoring data from 6 stations during dry season in 2005 in the Modaomen water way. The average value of salt intrusion length to the point where the salinity on the cross section is 0.5‰ is 37.0 km. When the projects of the water transfer to meet the emergency stemming from salty tide put into effect, the salt intrusion length is decreased, which is 20.7 km on average. According to the length which is predicted by the model, we establish two optimal regression equations for the discharge-salt intrusion relationship at slack after flood tide during dry season (using the calculated length and measured length to discharge, respectively), one is an exponential regression equation, \( x_{L0} = 104.13 e^{-0.0007Q} \) \( (R^2=0.8276) \); the other is a power-law regression equation, \( x_{L0} = 106 Q^{-1.401} \) \( (R^2=0.8007) \). Our results suggest that the salt intrusion length is dependent on the river discharge. The two regression equations used to determine discharge in the Modaomen water way which can explain river discharge-salt relationships, and offer a useful tool for predicting the relationships between estuarine salinity and river freshwater discharge.

© 2010 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.

Keywords: Salt intrusion; Freshwater discharge; Modaomen waterway; Pearl River estuary

1.1. Introduction

Salt intrusion in many estuaries is serious as result of the impact of global climate change and intensive anthropogenic activities [1]. In common with many estuaries, river channel has a gradual narrowing by exponentially of the banks away from the mouth, which is called as a funnel-shape [2, 3]. The mean flow speed seaward at any point along the channel will increase with distance inland. Because the flow is equal to the river

* Corresponding author. Tel./fax: + 86 10 58802079. 
E-mail addresses: cuibs67@yahoo.com, cuibs@bnu.edu.cn (B.S. Cui).
discharge divided by the cross-sectional area [2]. It is believed that the resistance of salt intrusion will increase with distance inland. Rivers deliver freshwater to estuaries and this freshwater delivery influences salinities in estuary waters. Savenije [4] had been derived an analytical relationship between the data of topography and salinity along the main shipping channel. This model is a one-dimensional steady state advection-diffusion equation for the funnel-shape estuary and has been successfully applied to many estuaries worldwide, including the Pungue estuary [2,5], Flushing Bay [6] and the Mekong estuary [3,7]. There are strong correlations between freshwater inflows and the salinity gradients in many estuaries. Brockway et al. [2] reported the negative relationship between the salt intrusion length and river discharge. Recently, the same result was found by others, like Sun et al. [8], Becker et al. [9] and Whitney [10]. The salt intrusion is proved to vary as the negative 1/7 power of the runoff in northern San Francisco Bay [11]. So we can consider that the intrusion length should vary as the inverse relationship of the runoff. However, a simple and effective relationship between the discharge and salinity along the river channel should be derived.

When the salt intrusion happened, the most effective solution is additional water that is required to prevent salt water from reaching some places like the intake during high water of spring tide. There are many studies that have investigated the freshwater discharge to block the salinity intrusion. Based on the salinity objectives for Yangzte Estuary, Sun et al. [8] had quantified to assess the impacts of changing freshwater inflow on the estuarine ecosystem. The freshwater discharge distribution over the branches of the Mekong Delta had been calculated by Nguyen et al. [7] by means of the analytical relationship that has been mentioned above. According to the relationship between salt intrusion length and different monthly discharges, the minimum required monthly river discharge at the upstream station can be calculated which can effective prevent salt intrusion [5].

In the Pearl River Delta of China, the Modaomen water way is the main source of drinking water for the cities of Jiangmen, Zhongshan, Zhuhai and Macao. The raw water intakes for drinking water are located at 18 km from the estuary mouth, Guadingjiao. During dry season the intrusion of salt water reaches the intake near the Zhuyin station, which causes the intake to be interrupted. This phenomenon may happen in the dry season during spring tide like year 2005. This problem has greatly affected the water supply to Zhuhai and Macao. In order to meet the demand of the urban domestic water, the authority firstly run the project of the water transfer to meet the emergency stemming from salty tide in Pearl River Delta channel networks during the dry season in 2005.

Our objective in this paper is to describe a simple and effective method, using the data of salinity and discharge to predicting the relationships of the discharge and salt intrusion length in the Pearl River estuary. Hereinafter, firstly, we apply the model to the one-dimensional steady state advection-diffusion equation for the funnel-shape estuary where the cross section decreases exponentially with distance inland, and calculate the salt intrusion length, which compare with the measured salt intrusion length. Secondly, using the calculated length and measured length, we can find that there is not only power-law function but also exponential function relationships of the discharge and the salt intrusion length, no matter how the length is calculated or measured. However, using the data of the calculated length, we can more effective predict the relationships of the discharge and salt intrusion length in the Pearl River estuary. It is also simple method which can be investigated for the problems experienced with the water transfer to the estuarine regions when the salt intrusion happened.

2. Study area

The Pearl River is one of the largest rivers in China, its deltaic region is characterized by a great number of tributaries and streams, forming a complicated watershed called Pearl River Delta within Guangdong Province. The Pearl River consists of three main tributaries-the North River, the East River, and the West River. The Modaomen water way is a mainstream outlet of the Xijiang River, the largest tributary of the Pearl River, China [12]. This water way is located downstream of the West River between latitudes 22°N and 22°40′N, and longitudes 113° E and 113°40′ E (Fig. 1). The water way has an average yearly runoff of 8.84×10¹¹ m², and accounts for 28.2% of the total water quantity discharged by the Pearl River [13,14]. When the discharge of the Xijiang lowers to about 2500 m³ s⁻¹ at the meeting site (Siquangao hydrological station) of the Xijiang river, and North of the Pearl River, the salt water intrusion will occur in the lower reaches of the Modaomen water way [15].

There where we choose six fixed gauging stations are Guadingjiao, Zhupaisha, Xihekou, Zhuyin, Ddao and Baiqing from the mouth to inland, which is about 0, 13.9, 22.9, 29.6, 44.5 and 49.1 km from the estuarine mouth, respectively, and the Cross-sectional area and other information can be seen to Table 1 and Fig. 1.

Table 1. General information of hydrological stations in the Modaomen water way
<table>
<thead>
<tr>
<th>Station name</th>
<th>Distance from the estuary mouth (km)</th>
<th>Cross-sectional area (m²)</th>
<th>Longitude</th>
<th>Latitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guadingjiao</td>
<td>0</td>
<td>14420</td>
<td>113°25' E</td>
<td>22°11' N</td>
</tr>
<tr>
<td>Zhupaisha</td>
<td>13.9</td>
<td>6160</td>
<td>113°21' E</td>
<td>22°17' N</td>
</tr>
<tr>
<td>Xihekou</td>
<td>22.9</td>
<td>9590</td>
<td>113°19' E</td>
<td>22°20' N</td>
</tr>
<tr>
<td>Zhuyin</td>
<td>29.6</td>
<td>7600</td>
<td>113°17' E</td>
<td>22°22' N</td>
</tr>
<tr>
<td>Daao</td>
<td>44.5</td>
<td>5620</td>
<td>113°13' E</td>
<td>22°30' N</td>
</tr>
<tr>
<td>Baiqing</td>
<td>49.1</td>
<td>5210</td>
<td>113°10' E</td>
<td>22°30' N</td>
</tr>
</tbody>
</table>

Fig. 1. Map of the Modaomen waterway

3. Analysis methods

Savenije [4,16] developed a model that predicts the salinity along the estuary axis depending on the shape of the estuary, the tidal influence and the river discharge. It is observed in a number of estuaries worldwide that the cross-sectional area decreases exponentially with distance inland from the mouth [2,4,5,6,7,17]. That is, we can write

\[ A = A_0 \exp(-\beta x) \]  

(1)

where \( A \) is the cross-sectional area from the estuary mouth, \( A_0 \) is the cross-sectional area at the estuary mouth (\( x=0 \)) and \( \beta \) is a decay coefficient, or estuarine tapering factor.
One of the purposes of this paper is to describe a simple method of predicting salt intrusion length according to the salinity at the gauging stations along the channel and freshwater discharge at upstream station. For part of the river estuary, there is relatively small change over time as a result of the mix of runoff in the salinity effect, so there often ignored advection diffusion equation of the time factor. That is, we can write:

\[
\ln \frac{S}{S_0} = - \frac{Q}{\beta K_x A_0} [\exp(\beta x) - 1] \tag{2}
\]

where \(S_0\) is the salinity at the estuary mouth, and \(\ln\) represents the natural logarithm. \(K_x\) represents the longitudinal salinity distribution coefficient, which is independent of the distance from the mouth, \(x\). According to Eq. (2), a plot of \(\ln (S/S_0)\) against \(\exp (\beta x)\) should produce a straight line with a slope \(-Q/(\beta K_x A_0)\) [2,18]. In the present case, Eq. (2) provides a good fit to the data we present in the next section, and so a \(K_x\), mixing coefficient, which is independent of \(x\) seems a reasonable assumption, at any rate up to the limit of salt intrusion.

There will take the limit of salt intrusion to be the point \((x = x_L)\) where the salinity equals its value in drinking water. There we take 0.5 ‰ of salinity as the critical value of the invasion, where the value of 0.5 ‰ recommended as the maximum for drinking water (salinity: 0.5‰, upper limit of drinking water in China) [19]. Rearranging gives the salt intrusion length as, we can write:

\[
x_L = \beta^{-1} \ln(1 - \ln(0.5/S_0) A_0 \beta K_x / Q) \tag{3}
\]

Notice that the intrusion length will increase with the size of the estuary mouth and with the mixing coefficient. It will decrease with increasing river discharge. The role of the tapering factor \(\beta\) in this regard is apparently ambiguous, although analysis shows that \(x_L\) will always decrease with increasing constriction of the estuary (increasing \(\beta\)), at least in all practical cases. More information can be referred the researches of Brockway et al. [2] and Savenije [20].

According to the results of Brockway et al. [2] and Savenije [20], this model will underestimate the saltwater intrusion, therefore we introduce a parameter, \(\phi\), to reduce this error, the Eq. (3) can be written as

\[
x_{L0} = x_L + \phi \tag{4}
\]

where \(x_{L0}\) is the calibrated intrusion length.

4. Data

Hourly mean high and low water levels, cross-sectional area and salinity data at 6 gauging stations from 18 January to 4 February 2005 were collected from 6 gauging stations along the Modaomen water way, Pearl River Delta. In general, all these stations sampled 1 m below the surface water which represent the salinity of surface water. The measurements were converted to salinity, because salinity is proportional to the chlorosity [21] and, this paper uses salinity to representative salt invasion. Location of the gauging stations and detailed information of the data can be referred to Fig. 1 and Table 1. We collected the data from Material achievements of synchronous hydrological and water quality monitor of West and East River Delta in dry season during 2005. The reliability and homogeneity of the hydrological and water quality data were strictly checked by the authority before they were released. There are using the network of fixed stations along the river banks, which measure salinity values hourly during the dry season. Nguyen and Savenije [3] found the maximum daily salinity values are close to the salinity of high water slack. These values are the average value of monitoring section surface salinity, which are easy to collect at each fixed station. Therefore we use the maximum daily salinity to replace the salinity of high water slack.

Since the water level at the Gaoyao station is influenced by the tide the recorded runoff especially in the dry season is considered unreliable and cannot be used. The tidal limit of Xijiang River has moved upstream in recent years, nearly Wuzhou station [22]. Therefore, the station Wuzhou, about 340 km from the estuary mouth (not show in Figure 1), has been used to estimate the river discharge. There are about three days to spend the water can arrive at the Modaomen waterway from the Wuzhou station. Therefore we use the peak discharge that is ahead of three days to calculate the saltwater intrusion. Savenije [4] demonstrated that the steady state salt balance equations for
high water slack situation. So, this study uses the maximum daily salinity at the period of the high water to represent the longest distance of saltwater intrusion. The measured lengths of salt intrusion in this paper are obtained from the contour map of the salinity at 6 stations during the measurements of 18 January to 4 February 2005.

5. Results

5.1. Salt intrusion

The convergence length, which is the length scale of the exponential function, is obtained by calibration of Eq. (1) against measured data. It can be seen very clearly in Fig. 2. The area of the mouth at high water $A_0$ has been measured as $14420 \text{ m}^2$, and the decay coefficient, $\beta$, has been determined by survey as $0.017 \text{ km}^{-1}$, the correlation coefficient, $R$, is more than 0.81.

The tides in the estuary are semi-diurnal and mainly come from the Pacific oceanic tidal propagation, which are also influenced by the geometry and bottom topography, meteorological factors and river discharge, with a microtidal one with only an average spring tidal range of $0.60-2.00 \text{ m}$ at the mouth (Fig. 3; [22,23,24]). The estuary is shallow and partially mixed, the deepest point at high water no more than 15 m, but mostly much shallower than this [23].

![Fig. 2. Shape of the Modaomen water way, showing cross-sectional area (m2) with the distance from the estuary mouth (km)](image_url)

$$y = 11907e^{-0.017x}$$

$R^2 = 0.6672$

![Fig. 3. Tidal level at Guadingjiao station during 09:00 on 18 January to 10:00 on 5 February 2005](image_url)
**Table 2. Values of parameters of saltwater intrusion in the study period**

<table>
<thead>
<tr>
<th>Date</th>
<th>Salinity at the mouth S₀ (%‰)</th>
<th>Discharge Q (m³/s)</th>
<th>Slope</th>
<th>R²</th>
<th>Mixing coefficient Kₓ (m²/L)</th>
<th>Salt intrusion length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Calculated Length</td>
</tr>
<tr>
<td>18/01/05</td>
<td>16.1</td>
<td>1450</td>
<td>-7.0</td>
<td>0.99</td>
<td>0.8</td>
<td>28.9</td>
</tr>
<tr>
<td>19/01/05</td>
<td>15.8</td>
<td>1440</td>
<td>-5.4</td>
<td>0.98</td>
<td>1.1</td>
<td>35.7</td>
</tr>
<tr>
<td>20/01/05</td>
<td>21.2</td>
<td>1470</td>
<td>-4.7</td>
<td>0.93</td>
<td>1.3</td>
<td>45.0</td>
</tr>
<tr>
<td>21/01/05</td>
<td>20.3</td>
<td>1550</td>
<td>-4.2</td>
<td>0.89</td>
<td>1.5</td>
<td>45.0</td>
</tr>
<tr>
<td>22/01/05</td>
<td>18.3</td>
<td>1790</td>
<td>-4.2</td>
<td>0.88</td>
<td>1.8</td>
<td>36.8</td>
</tr>
<tr>
<td>23/01/05</td>
<td>16.3</td>
<td>1790</td>
<td>-5.1</td>
<td>0.94</td>
<td>1.4</td>
<td>37.5</td>
</tr>
<tr>
<td>24/01/05</td>
<td>16.0</td>
<td>1630</td>
<td>-5.2</td>
<td>0.96</td>
<td>1.3</td>
<td>36.8</td>
</tr>
<tr>
<td>25/01/05</td>
<td>16.0</td>
<td>1540</td>
<td>-5.1</td>
<td>0.97</td>
<td>1.2</td>
<td>37.4</td>
</tr>
<tr>
<td>26/01/05</td>
<td>14.7</td>
<td>1650</td>
<td>-8.1</td>
<td>0.98</td>
<td>0.8</td>
<td>25.0</td>
</tr>
<tr>
<td>Average</td>
<td>18.02</td>
<td>1628</td>
<td>-5.4</td>
<td>0.95</td>
<td>1.3</td>
<td>37.0</td>
</tr>
<tr>
<td>27/01/05</td>
<td>18.3</td>
<td>2330</td>
<td>-10.8</td>
<td>0.99</td>
<td>0.9</td>
<td>20.6</td>
</tr>
<tr>
<td>28/01/05</td>
<td>19.0</td>
<td>2820</td>
<td>-13.4</td>
<td>0.98</td>
<td>0.9</td>
<td>17.3</td>
</tr>
<tr>
<td>29/01/05</td>
<td>13.5</td>
<td>3030</td>
<td>-13.5</td>
<td>0.98</td>
<td>0.9</td>
<td>15.7</td>
</tr>
<tr>
<td>30/01/05</td>
<td>10.4</td>
<td>3080</td>
<td>-13.2</td>
<td>0.99</td>
<td>0.9</td>
<td>14.8</td>
</tr>
<tr>
<td>31/01/05</td>
<td>10.8</td>
<td>2990</td>
<td>-19.7</td>
<td>0.99</td>
<td>0.6</td>
<td>10.4</td>
</tr>
<tr>
<td>01/02/05</td>
<td>12.3</td>
<td>2820</td>
<td>-13.7</td>
<td>0.99</td>
<td>0.8</td>
<td>15.1</td>
</tr>
<tr>
<td>02/02/05</td>
<td>16.5</td>
<td>2440</td>
<td>-10.2</td>
<td>0.97</td>
<td>1.0</td>
<td>21.2</td>
</tr>
<tr>
<td>03/02/05</td>
<td>14.4</td>
<td>1970</td>
<td>-5.3</td>
<td>0.98</td>
<td>1.5</td>
<td>35.1</td>
</tr>
<tr>
<td>04/02/05</td>
<td>13.7</td>
<td>1570</td>
<td>-5.1</td>
<td>0.98</td>
<td>1.2</td>
<td>35.6</td>
</tr>
<tr>
<td>Average</td>
<td>14.4</td>
<td>2470</td>
<td>-11.7</td>
<td>0.99</td>
<td>1.0</td>
<td>20.7</td>
</tr>
</tbody>
</table>

a: The measured lengths are obtained from the contour map of the salinity of 6 stations during the measurements of 18 January to 4 February 2005.

This paper uses the statistic salinity distributions and the parameters for the geometry of estuary at the gauging stations. Eqs. (2) and (3) can be used to calculate the longitudinal variation of the salt intrusion. We find the calculated results are underestimated the saltwater intrusion compared to the measured length. So we use the Eq. (4) to calibrate the calculated length. We use the average relative error between the calculated and measured length to calibrate, and the Eq. (4) can be written as:

$$x_{L0} = x_L + 0.22x_L = 1.22x_L$$

(5)

The calculated results are presented in Table 2. As showing in Table 2, we can see that the salt intrusion length is shorter after starting the project of the water transfer to meet the emergency stemming from salty tide, which have shown positive results at 26 January 2005. Before the project (from 18 to 25 January), the correlation of plot of ln ($S/S_0$) against exp ($\beta x$) is more than 0.96 and the average slope $-Q/(\beta K_x A_0)$ is -5.4. The average mixing coefficient, $K_x$, is 1.3. However, when the project was showing positive results, the average slope and $K_x$ were -11.7 and 1.0, respectively. The mean location of the 0.5 ‰ salinity contour based on the Eq. (4) at flood tide slack before and after the project were 37.0 km and 20.7 km, respectively, upstream of the origin at Guadingjiao station (The measured length of salt intrusion were 41.3 km and 22.7 km, respectively) (see Table 2).
Fig. 4. Plot of the salt intrusion length (the distance inland at which salinity reaches 0.5‰) against river discharge. The curved line shows the theoretical relationship between these quantities for the mean dispersion coefficient observed in the Pearl River estuary. Note that there is the (negative) nonlinear relationship between the river discharge and salt intrusion length. Where \( x_{L0} \) and \( Q \) represent the saltwater intrusion length and freshwater discharge, respectively. Fig. 4a & b represent the relationships of discharge and salt intrusion length on the calculated length and measured length, respectively. The curve (blue) represents power-law curve and the black is exponential curve.

5.2. Relationship between discharge and salinity intrusion

The range of river discharge at Wuzhou station was from 1450 to 1790 m³/s, and the average was 1628 m³/s during 18 to 25 January 2005, and the range was between 1570 to 3080 m³/s, the average was 2470 m³/s after the water transfer project implementation (see Table 2). The relationship between along channel salinity intrusion and river discharge is shown in Fig. 4. The exponential coefficient of determination when use the calculated length to fit is greater than power-law coefficient (\( R^2 = 0.8007 \) and 0.8276, respectively), which is optimal to the situation using the measured length to fit (\( R^2 = 0.7516 \) and 0.7807, respectively).

When the river discharge was low during 18 to 25 January 2005, about 1628 m³/s, the location of salt intrusion was reaching far more than the Zhuyin station. However the river discharge was increased to 2470 m³/s, the location of salt intrusion was downstream, which was near the middle of Zhupaisha station and Xihekou station.

Results from Fig. 4a and b indicate the estuarine salinity response to freshwater input is largely dependent upon the peak in river discharge relative to base flow. The optimal (exponential) regression equation for the discharge-salinity intrusion relationship at slack after flood tide is:

\[
x_{L0} = 104.13e^{-0.0003Q} (R^2 = 0.8276)
\]  

where \( x_{L0} \) is salinity intrusion length (km) after calibrated relative to the Guadingjiao station near the mouth, \( Q \) is the peak discharge at the upstream station (Wuzhou station) (m³/s).

However, the optimal (power-law) regression equation for the discharge-salt intrusion relationships at slack after flood tide is:

\[
x_{L0} = 1 \times 10^6 Q^{-1.401} (R^2 = 0.8007)
\]  

where the parameters are same as above.

6. Discussion

The assumption made in the study to arrive at the steady state equation. Savenije [4] derived an expression equation to investigate how quickly an estuary system adjusts to a new situation, if the response time to adjust is not too long the steady state model may be used. We computed the system response time for the Pearl River estuary. The computed average system response times for Modaomen water way is about 9 days during 18 January to 4 February 2005, which indicates that the estuary system is capable of adjusting itself to a new situation in a no long time. Therefore we can use the steady state method to compute the salt intrusion in the Pearl River estuary. And then we use the result of the model to establish a simple and optimal relationship of discharge-salinity.
6.1. Comparison of calculated length with measured length

During the measurements of 18 January to 4 February 2005 the salt intrusion is underestimated by the model in the most upstream part of the estuary, even though the calculated lengths were calibrated (Table 2 and Fig. 5). The average length of saltwater intrusion is about 37.0 km according to the model predicts before the implementation of the water transfer project. The salt intrudes more far than the model predicts. This intrusion length is more inland than the result of Chen et al. [23], because there are difference at the salinity and cross-sectional area. The correlation of plot of \( \ln(\frac{S}{S_0}) \) against \( \exp(\beta x) \) is more than 0.95 and the average slope \(-\frac{Q}{\beta K_0A_0}\) is great less than the result of Chen et al. [23]. However, mixing coefficients, \( K_x \), are almost similar to the conclusions of Chen et al. [23], but the value is slightly different. The underestimated intrusion length is less than 10 km. The relative errors alter from 0.0 % to 11 %, and the average relative error is 1.9 %. During the implementation of the water transfer project, the relationship of the calculated length and the measured length is similar to before the project (Table 2 and Fig. 5).

It was observed by Chen et al. [23] that there are at least four small water ways, like Shiqi water way, along the Modaomen water way from the Baiqing station to the Guadingjiao station, which can carry high salinity saltwater into the Modaomen water way when the river discharge is small. Graas and Savenije [5] found that sand banks in the Pungue estuary blocked the intrusion of saline water. On the contrary, we can see that there are many central shoals which will effect as natural barriers which slow down the ebb tide discharge. These central shoals separate the river channel and make the channel to narrow down. A velocity maximum occurred within the halocline during the early flood and trapping of high-salinity waters occurred on the ebb [25]. Therefore, the high-salinity waters will more or less stay at the upstream of the estuary to higher the salinity of river water when the flood tide happened. During the implementation of the water transfer project, the freshwater can be replenished through those small water ways which connect with the Modaomen water way. These replenished freshwater can effectively restrict the salinity intrusion.

Moreover, this simulation model is simple and demonstrated by many authors at different estuaries around the world [2,3,4,5,18,23,26], which is established on the steady state salt balance situation. There suppose that the cross-sectional area decreases exponentially with distance inland from the estuary mouth. No matter how, this sample model can effectively predict the length of saltwater intrusion in some ways (see Table 2 and Fig. 5). It can be sure that it is a proper monitoring method to evaluate length of the saline water intrusion, which also is available in the Modaomen water way, when the salinity at the mouth and discharge at upstream are known.

![Fig. 5. Comparison of calculated length with measured length during 18 January to 4 February 2005](image)

Deviations from predicted values may be attributed to effects of variable bathymetry on the computed salt intrusion length [11]. The mean flow seaward at any point along the channel will increase with distance inland, and associated increases in longitudinal salinity gradients, density-driven flow may strengthen, and the upstream transport of salt may be larger than theory prescribes [9]. This result is in according with the model predicted values
and measured values. The coefficient of regression equation \( R^2 \) is 0.9664 (Fig. 5), therefore, it is believed that lengths of the model predict are reliable against the measured length, even though there are certain underestimated. This method was proved by the study of [23]. Even though, their results of the length of salt intrusion are quite low, they used the different monitoring sections and different dates of observed data which is quite smaller than this study.

6.2. Salinity intrusion variability under different river discharge

The measurement of freshwater discharge is crucial to interpretation of the salinity data [11]. The key of the problem is that in the most tidal delta the freshwater discharge is often quite smaller than the tidal flows, thus resulting in direct gauging of outflow impractical. Therefore we use the upstream freshwater discharge which is not influenced by the tide to calculate the length of salt intrusion. According to the results we calculated, the discharge-salt intrusion relationship is got at Section 5.2 (Eqs. (6) and (7)).

For the base-flow conditions (during which discharge is small and closes to \( Q = 0 \)), the salt intrusion approaches a location close to 83.5 km upstream of Guadingjiao station. The rate constant in the exponential form of the regression relationship is -0.0007 (Eq. 6). The salt intrusion varies (with discharge) at a rate proportional to its position in the estuary. Such as, when the \( Q \) is close to zero and the salt intrusion length is close to 104.13 km, the change in the length of the salt intrusion is approximately 0.07 km per unit discharge. If \( Q \) is the maximal discharge (3080 m³/s) during the project of the water transfer and the length of the salt intrusion is approximately 14.8 km upstream of Guadingjiao station, the length of the salinity intrusion changes approximately 0.008 km per unit discharge. This negative exponential relationship of the salt-discharge relations is found in the Cape Fear River [9], and the length of the salt intrusion changes is different at the low discharge and high discharge. Because the length of salt intrusion decreases, the longitudinal salinity gradient increases and causing each unit increase in discharge to be less effective in moving the intrusion farther downstream [9].

Power-law regression analysis indicated that the salt intrusion length is proportional to discharge to the 1/7 power (\( x_L \sim Q^{-1/7} \)), this relation, which differed from the standard 1/3 power [11]. A power-law exponent is approximately -1/5 in the Cape Fear River [9]. However, in this paper the power-law exponent is approximately -14/10 (Eq. 7), which means that this more strong dependence of salt intrusion on discharge than the results of studies above.

There are several limitations in this study. There lack of enough fixed monitoring sections along the river bank except the Modaomen water way, and these fixed sections measure salinity values during the dry season. The topography of the Pearl River Delta is continuously changing due to sand excavation activities throughout the Pearl River Delta region [27]. It is necessary to update the data of geometrical variation in the riverbed. More uniform distribution of cross section along the river channel is needed to calculate more accurate result. Therefore, there is still room for improvement of the salinity model by using more systematic monitoring data and real time information of topographical data. There is an inflection point in the decay of area with distance at about 20 km inland from the mouth (Table 1). Brockway et al. [2] and Chen et al. [23] noted the inflection point in their study. This inflection point will more or less affect the value of tapering factor, \( \beta \). According to the data we collect, the cross-sectional at the estuary mouth, Guadingjiao, is not at the end of the Modaomen water way. However the method is common if the location of estuary mouth is changed. The distance is but a relative distance.

7. Conclusions

This paper presents a new approach to establish a simple and optimal discharge-salinity relationship by means of the calculated length of seawater intrusion and the discharge at upstream station of the Pear River Delta during dry season a sample predictive analytical salt intrusion model. The upstream station, Wuzhou, is not influenced by the tide all year round. The results of model agree well with measured data and are effectively estimating the length of seawater intrusion. This study shows that with the topographical and salinity characteristics of the channels in Pearl River Delta, it is possible to calculate a well result of length of salinity intrusion and the freshwater discharge at the upstream station of the Pear River Delta. Furthermore, this paper summarizes the optimal relationships of discharge-salinity intrusion in Modaomen waterway by comparing the regression equations.

The salt intrusion in the Modaomen water way can be adequately modeled using the theory of Savenije [4,15]. There can be used the data of the topographical characteristics (like cross-sectional area) of fixed monitoring stations along the channel to estimate the length of salt intrusion, when the salinity at the mouth and discharge at
upstream are known. The lengths of the model predict are reliable against the measured length. The average length of saltwater intrusion is about 37.0 km according to the model predicts before the projects, while the length is 20.7 km during the period of projects. So the water transfer projects can effectively mitigate the salt intrusion in a way.

The optimal exponential regression equation and the power-law regression equation for the discharge-salt intrusion relationships at slack after flood tide can be created from the freshwater discharge and salt intrusion length (comparing the calculated length and measured length). Therefore, as long as we get the data of the discharge at upstream of the estuary and salt value at the river mouth, the length of the salt intrusion can be calculated by the Eqs. (6) or (7). On the contrary, according to the length of salt intrusion, the minimum daily discharge to prevent the salt water can be predicted. The two optimal regression equations can estimate the salinity intrusion and river discharge quickly and simply, which provide a decision-making basis for quick response to deploy the corresponding preventive measures to minimize disasters when the salt intrusion happened. This sample predictive model is an effective tool to analyze the salt intrusion and freshwater discharge distribution in delta regions.

Acknowledgements

This study was funded by the National Natural Science Foundation (U0833002; 50939001) and National Key Basic Research Project of People’s Republic of China (2003CB415104). We also acknowledge the contributions of the reviewers of this manuscript and the authors wish to express great thanks to anonymous reviewers and editors for their time and efforts.

References


